2022 TDM Review: CPE-NASA PPUP

Presenter: MT/ Eric Pencil
Moderator: LTS/ Thomas Liu
NASA Glenn Research Center

March 1, 2022

PPUP Team Members

Colorado Power Electronics

- *PPU Development / Fabrication / Testing*
  - Geoff Drummond
  - Kevin O'Connor
  - Daniel Powell
  - Vlad Shilo

NASA (Management)

- *MSFC (Mission Management)*
  - Andrew Schnell
- *GRC (Project Management)*
  - Eric Pencil (MT)
- *GRC (Project / Technical Guidance)*
  - Dave Jacobson (LTS)
  - Tim Smith (MT)
  - Carol Tolbert (MA)

NASA (Technical)

- *GRC (PPU Functional / Integrated Testing)*
  - Hani Kamhawi (LTS)
  - Thomas Liu (LTS)
  - Paul Nowak (LEM)
  - Todd Peterson (LEX)
  - Luis Piñero (LTS)
  - Corey Rhodes (LTS)
- *GRC (PPU Environmental Testing Liaisons)*
  - Mike Garrett (LED)
  - Kenneth Pederson (LMD)
  - Vicente Suarez (LMD)

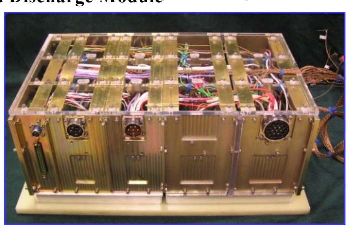
CPE-NASA Public-Private Partnership (1/2)

- Since 2003, NASA has awarded Colorado Power Electronics (CPE) 11 SBIR (Small Business Innovation Research) grants to develop and mature power processing unit (PPU) technologies for a variety of electric propulsion (EP) needs.

- In 2005, CPE began work on a high-performance PPU architecture that would support missions utilizing a variety of NASA and commercial Hall-effect thrusters (HET) in the popular 5-kW power class, including the NASA HiVHAc (High-Voltage Hall Accelerator).

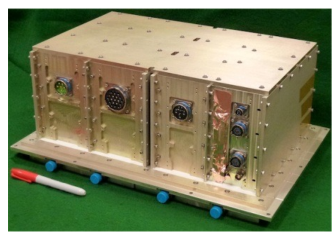
1-kW Breadboard Discharge Module

1st application of full-resonant power converter to kW-class EP



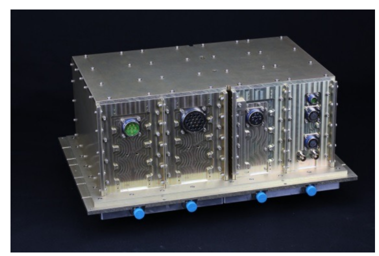
Brassboard PPU #1

Tested for >1,000 hr in vacuum environment at GRC



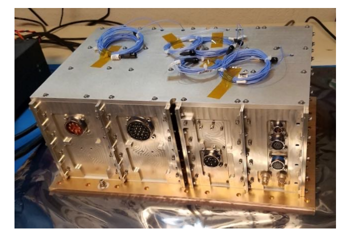
Brassboard PPU #2

Performance characterized at GRC in thermal-vacuum tests with integrated demonstrations using HiVHAc and Maxar SPT-140



Engineering Model (EM) PPU

Mechanical, thermal, radiation, worst-case, and reliability analyses completed



PDU PPU

CPE-NASA Public-Private Partnership (2/2)

- Now nearing the end of a SBIR Phase III effort with NASA GRC and JPL, CPE has delivered a high-fidelity, flight-like Prototype Development Unit (PDU) PPU to NASA.
- At GRC, the PDU PPU will undergo functional / performance checkouts, integrated system tests (IST), and qualification-level environmental testing (i.e., electromagnetic interference / compatibility, vibration / pyroshock, and thermal-vacuum) to verify that the CPE design meets anticipated NASA mission requirements.

PPUP (ACO)

VF-11
Pre-Environmental Checkouts & IST

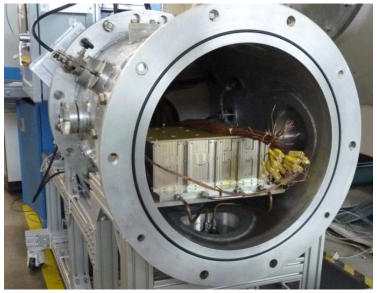
In Progress

Starts in March 2022

SBIR Phase III

Electromagnetic Interference Lab

Structural Dynamics Lab



VF-70 thermal-vacuum chamber

PPUP (ACO)

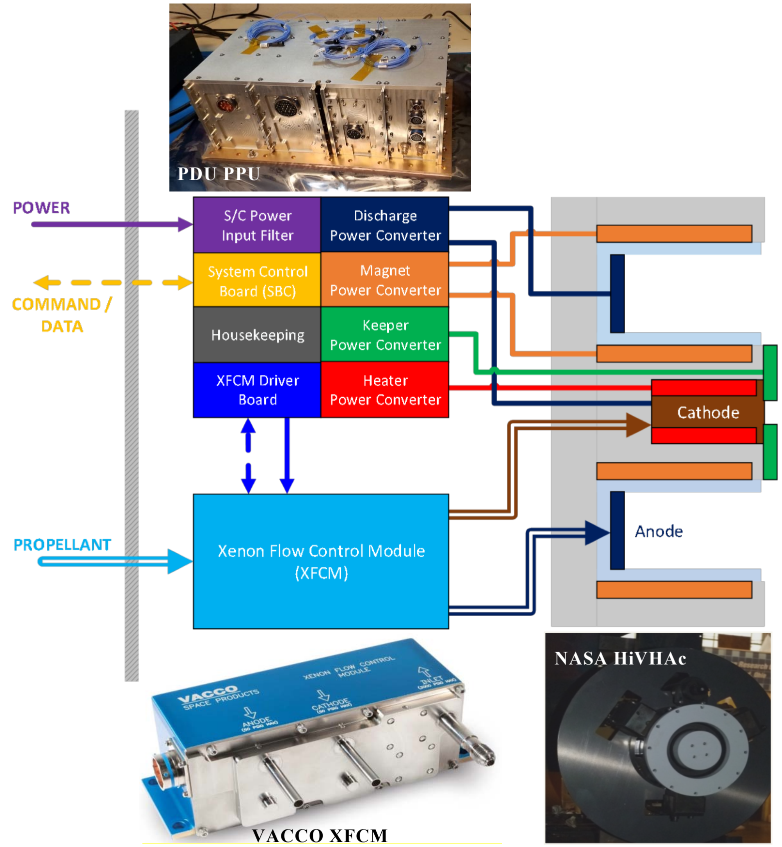
VF-11
Post-Environmental ISTs

Starts in July 2022

ACO Objectives (1/4)

The ACO (Announcement of Collaborative Opportunity) effort will utilize GRC EP test facilities to:

- Verify CPE PDU PPU integrated performance when operated as part of a complete HET system
- Demonstrate CPE PPU compatibility with thrusters from NASA and prospective commercial customers
- Advance the CPE HET PPU technology readiness level (TRL) to ~TRL 6 to encourage mission infusion
- Provide CPE with PDU PPU performance data and operational lessons learned to refine technology's commercialization plan and to showcase the technology to prospective NASA and commercial end-users



ACO Objectives (2/4)

The ACO (Announcement of Collaborative Opportunity) effort will utilize GRC EP test facilities to:

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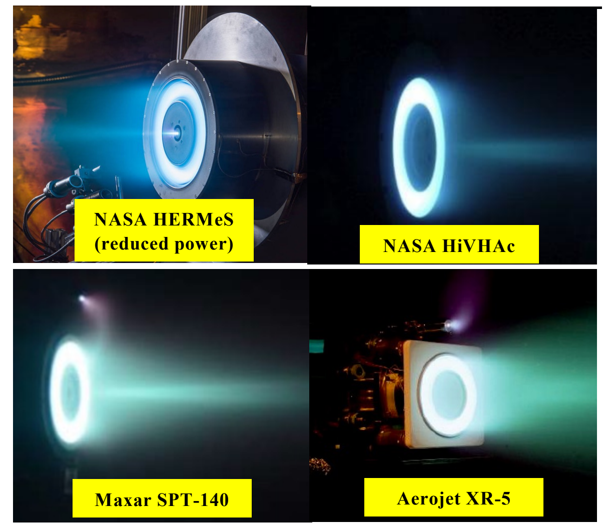

PPU Features

- ❖ Wide output ranges to enable operation of multiple thrusters
- ❖ Modular construction with parallel discharge modules scalable to higher powers
- ❖ Independent discharge module control for high efficiency at low power

ACO Objectives (3/4)

The ACO (Announcement of Collaborative Opportunity) effort will utilize GRC EP test facilities to:

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PDU PPU	Discharge	Magnets (2)	Keeper	Heater
Output Voltage	200 – 700 V	1 – 20 V	1 – 40 V	1 – 13 V
Output Current	1.4 – 15 A	1 – 7.5 A	1 – 2 A	3.5 – 21 A
Output Power Max	4.5 kW	108 W	80 W	210 W
Regulation Mode	Voltage or Current	Current	Current	Current
Output Ripple	≤ 5%			
Line/Load Regulation	≤ 2%			
Input Voltage	68 – 140 V (main) and 24 – 34V (housekeeping)			

Note: Improvements since EM PPU are shown in red

PPU Features

- Wide input ranges to satisfy power requirements for both commercial spacecraft buses and NASA missions
- Discharge supply delivery of full power with >95% peak efficiency at all input / output voltage settings

ACO Objectives (4/4)

The ACO (Announcement of Collaborative Opportunity) effort will utilize GRC EP test facilities to:

- Verify CPE PDU PPU integrated performance when operated as part of a complete HET system
- Demonstrate CPE PPU compatibility with thrusters from NASA and prospective commercial customers
- Advance the CPE HET PPU technology readiness level (TRL) to ~TRL 6 to encourage mission infusion
- Provide CPE with PDU PPU performance data and operational lessons learned to refine technology's commercialization plan and to showcase the technology to prospective NASA and commercial end-users

PPU Features

- Digital control interface unit (DCIU) with space-qualified, rad-hard, reprogrammable FPGA (field-programmable gate array) and autonomous system control algorithms
- Power, telemetry, and control interfaces for VACCO XFCM
- Discharge ripple current telemetry to assess thruster stability
- Magnet reversal relay to allow for roll torque cancellation
- Safety interlocks and lockouts for discharge and heater supplies
- Rad-hard components rated to total ionizing dose (TID) of 100 krad and linear energy transfer (LET) of 37 MeV-cm^2/mg
- Assembly via flight parts with flight processes and procedures

Key Challenge in 2020/2021: COVID-19

CPE-NASA PPUP

Schedule delay for PDU PPU assembly

- Status: Resolved in November 2020 (schedule impact: ~7 months)

- COVID-19 disruptions led to supply chain delays for various PDU PPU components.

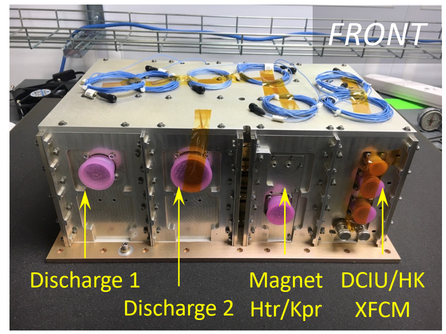
Schedule delay for PDU PPU delivery and test activities at GRC

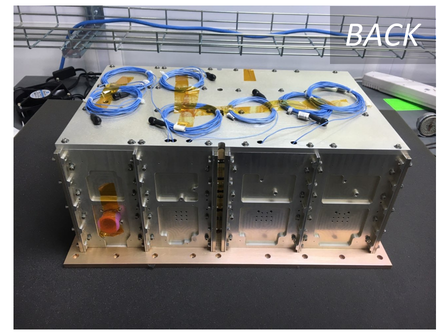
- Status: Resolved in Sept/Oct 2021 (schedule impact: ~11 months; budget impact: ~18 months of NASA labor)

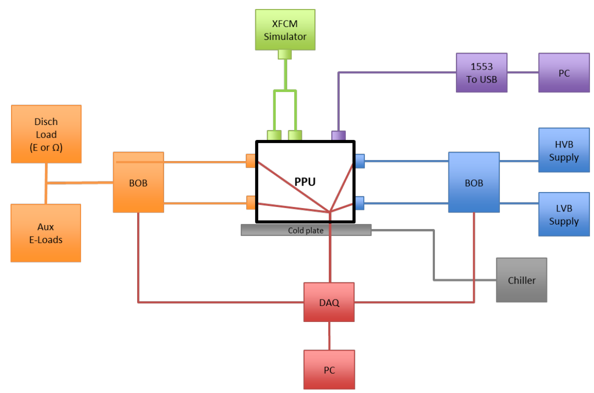
- NASA GRC reopening was slow-paced but deliberate.
- Center access is no longer a significant problem. GRC is at 50% occupancy with lab workers getting sufficient access during week.

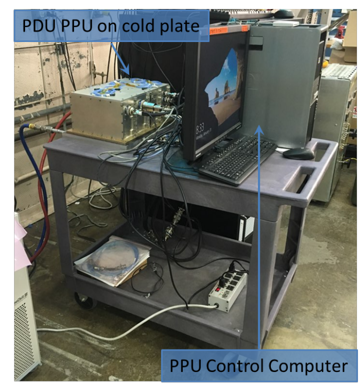
Key 2021 Accomplishments

- ✓ [CPE] Completed assembly-level functional testing of PDU PPU prior to GRC delivery
- ✓ [GRC] Completed benchtop functional / acceptance testing of PDU PPU
- ✓ [GRC] Refurbished and re-activated VF-11 test facility to support pre- and post-environmental integrated system testing
- ❖ Final checkouts of VF-11 and pre-environmental IST buildup is nearing completion









Benchtop Functional / Acceptance Testing

Test Objective:

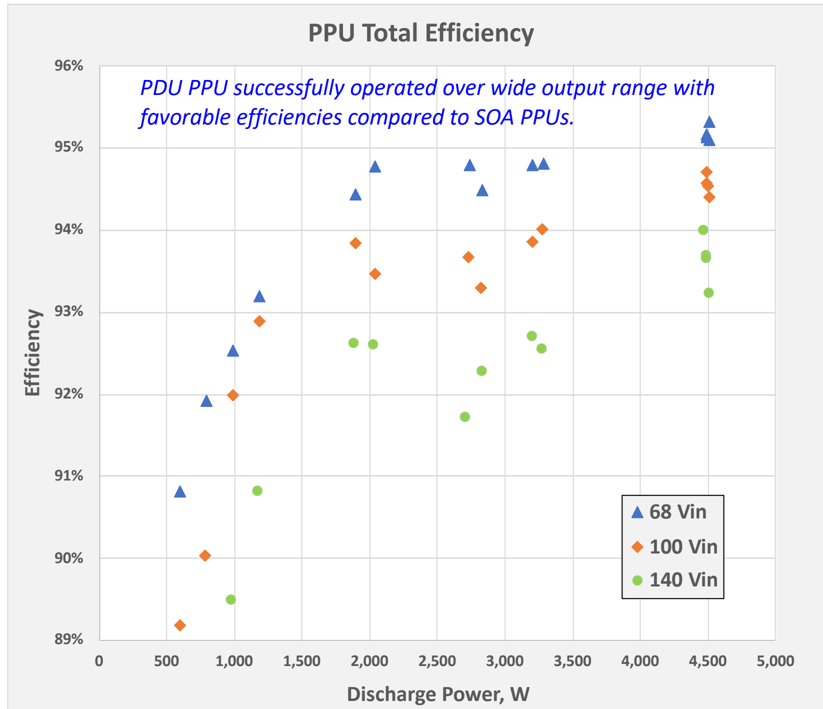
Collect data to verify PDU PPU requirements, characterize performance, and identify problems or deficiencies

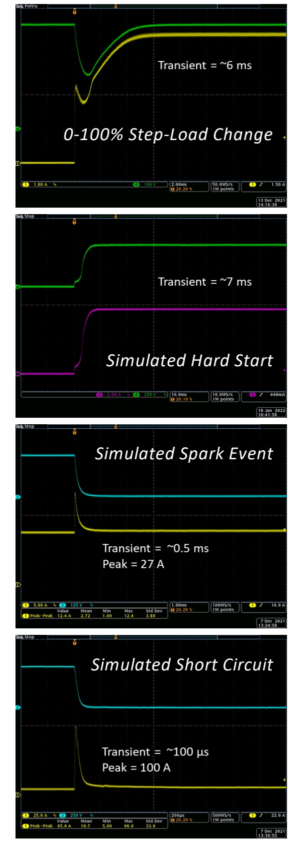
Data Collection:

- Isolation
- Operating range
- Ignitor
- Regulation
- Efficiency
- Telemetry
- Setpoints
- Idle Power
- UV & OV
- Output Faults
- Transient Behavior
- Safety Interlocks
- XFCM

Requirements Verification:

All tested electrical performance, functional, and isolation requirements were successfully verified





Right: PDU PPU discharge supply displayed excellent transient behavior during load changes, simulated startups, and simulated faults.

CPE-NASA PPUP

Pre-Environmental IST

Test Objective:

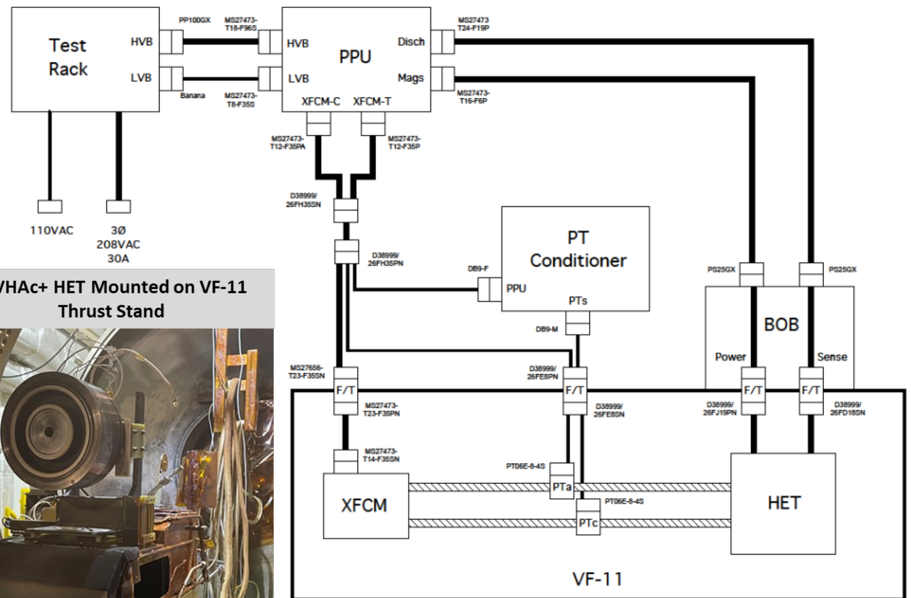
Demonstrate PDU PPU compatibility and functionality, verify performance, and collect baseline pre-environmental data when operated as part of an integrated 5-kW EP string

Test Segments:

1. Thruster bakeout (i.e., open-loop): PPU & lab propellant feed system
2. Discharge current closed-loop: PPU & XFCM
3. Pressure / flow closed-loop: PPU & XFCM
4. Fault testing: PPU fault impacts on HET & XFCM hardware

Challenges:

- COVID-related supply chain delays
- Center closings due to adverse weather



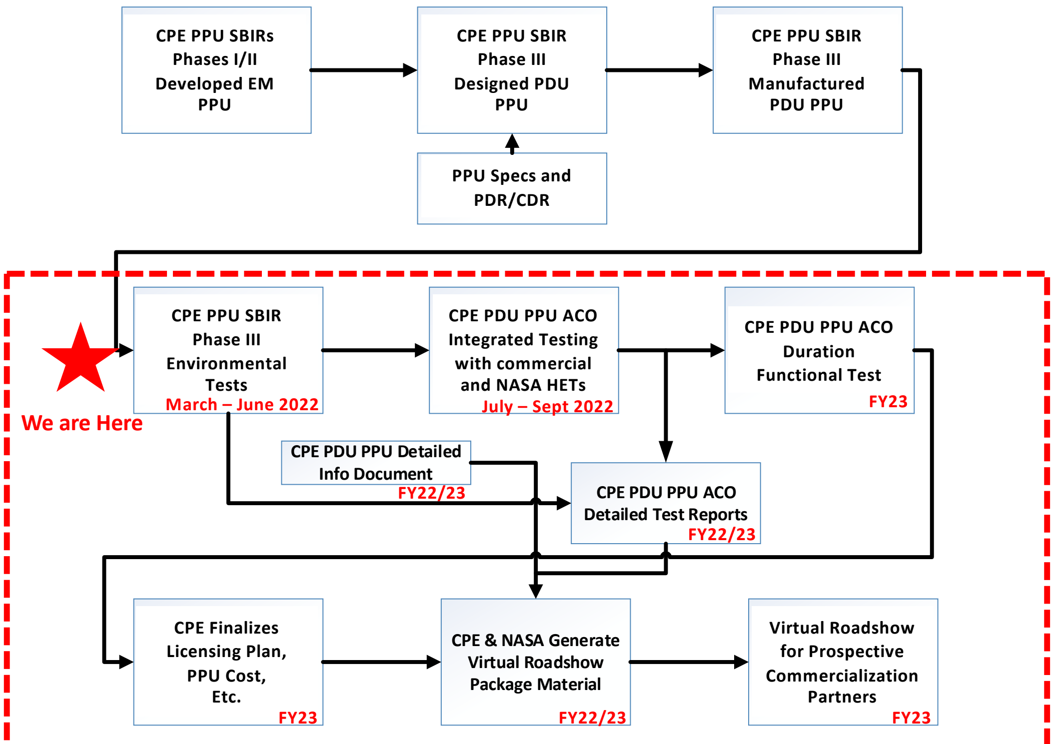
HiVHAc+ HET Mounted on VF-11 Thrust Stand

Final facility and test setup checkouts are in progress. Positive schedule margin exists for completion of pre-environmental IST in March 2022.

CPE-NASA PPUP

CPE PPU Commercialization Roadmap

- CPE designed the PPU, performed all parts selection, and procured all components.
- CPE sub-contracted flight-certified contractor (DBM Technologies) to assemble the PPU in accordance with IPC-A-610 standards.
- CPE performed functional testing of the PDU PPU prior to delivery to NASA GRC.



- NASA GRC is supporting functional, performance, environmental, and integrated tests of the PDU PPU.
- NASA GRC has completed benchtop functional / acceptance testing of the PDU PPU; pre-environmental IST is in progress.
- CPE and NASA will jointly complete all analyses and test reports to prepare "roadshow" package to brief prospective end-users.

Commercialization Plan Activities

- ❑ CPE to formulate a licensing / partnership strategy with potential partners
- ❑ CPE and NASA to identify any "gaps" that remain to flight-qualify the CPE PPU design and build
- ❑ CPE to develop its projected schedule and cost for manufacturing a flight-unit PPU
- ❑ CPE and NASA to prepare a full set of "key" documents, including requirements, specifications, bill of materials, analyses, qualification test reports, and integrated test reports
- ❑ CPE and NASA to compile presentation material for a "Virtual Roadshow" with non-disclosure agreements (NDA) required from interested parties:
  - "Key" documents
  - Main CPE PPU design features
  - Summary of select commercial and NASA design reference mission (DRM) studies implementing the CPE PPU
  - Etc.
- ❑ CPE and NASA to engage commercial companies that have already indicated interest in the CPE PPU technology, including prime contractors, spacecraft bus providers, and electric propulsion developers

2022 Project Outlook

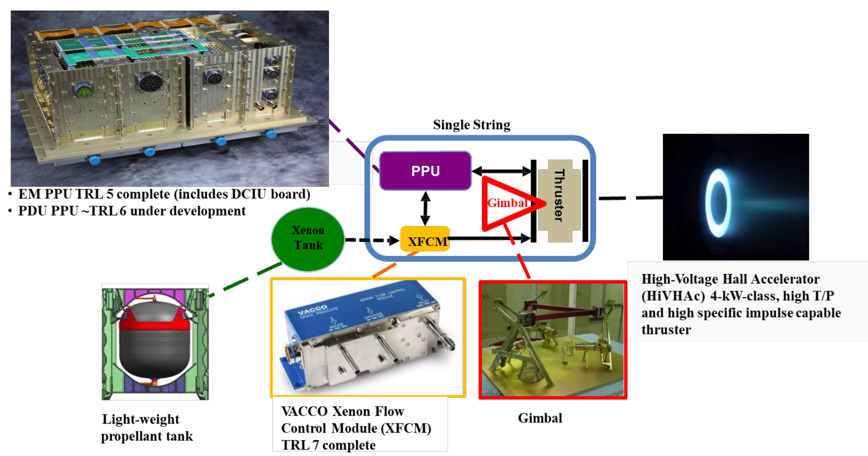
Fiscal Year 2022 (FY22)

- Key Risk: PPUP replan to maintain full technical content is not approved by TDM. Additional budget and schedule resources will be needed to complete all technical tasks. An extension of SAA period of performance into FY23 will be needed.

- PPUP ACO project has extended the SAA period of performance through the end of FY22.
- Testing in FY22 would seek to complete post-environmental integrated testing with commercial and NASA thrusters.
- Testing in FY23 would include a duration functional test to assess the viability of a complete electric propulsion string utilizing the PDU PPU.

Conclusion

- The PPUP ACO effort is the culmination of a decade-long NASA investment in the CPE HET PPU technology.
- Successful formulation and execution of replanned FY22 and FY23 work are expected to yield a highly-capable, ~TRL-6 PPU technology to support NASA and commercial 5-kW HET system needs.



Key PPU Features

- Wide input / output ranges at high efficiency
- Modular construction with power scalability
- Rad-hard flight parts assembled with flight processes
- Autonomous system control algorithms with thruster stability monitoring and safety features
- Magnet reversal capability for roll torque cancellation
- Default compatibility with VACCO XFCM

Key Mission Benefits Anticipated

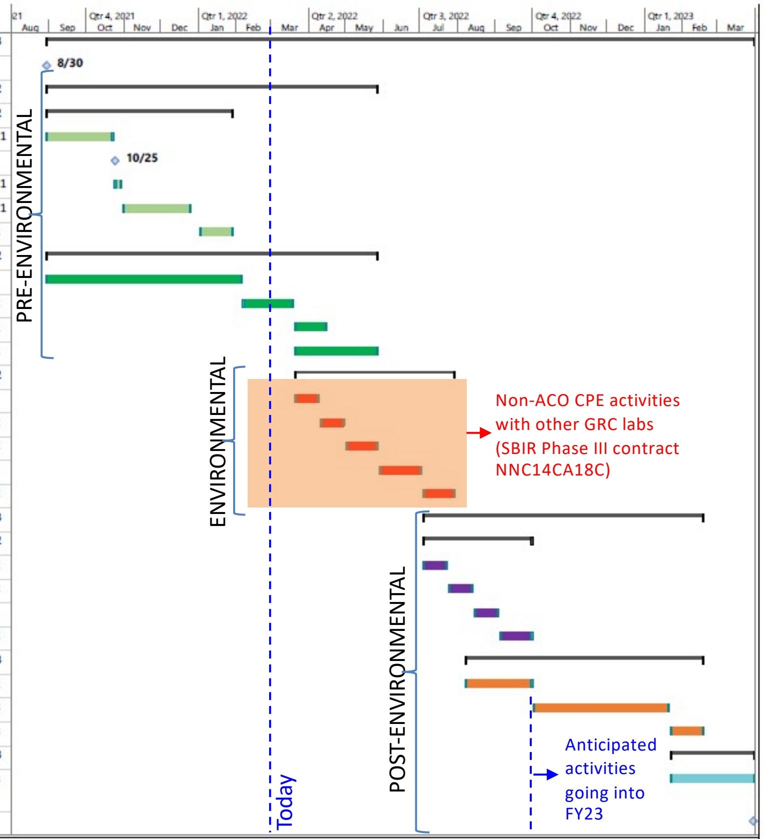
- High performance and flexible compatibility with different spacecraft buses and thrusters
- Wide operating range to accommodate deep thruster throttleability for closing more missions
- Modular, light-weight (low kg/kW) design to facilitate high-power electric propulsion systems
- Comprehensive PPU design without need for additional subsystem development

Supplemental Slides

Tentative Replanned Project Schedule

CPE-NASA PPUP

ID		Task Mode	Task Name	Duration	Start	Finish
1			**PPUP**	**415 days?**	**Mon 8/30/21**	**Fri 3/31/23**
2			Onsite ATP		Mon 8/30/21	
3			**PRE-ENVIRONMENTAL TESTIN**	**195 days?**	**Mon 8/30/21**	**Fri 5/27/22**
4			**Benchtop acceptance**	**110 days?**	**Mon 8/30/21**	**Fri 1/28/22**
5			GSE buildup	8 wks	Mon 8/30/21	Fri 10/22/21
6			PDU delivery to GRC [CPE		Mon 10/25/2	
7			PDU ops training	1 wk	Mon 10/25/2	Fri 10/29/21
8			Benchtop functionals	8 wks	Mon 11/1/21	Fri 12/24/21
9			Test report	4 wks	Mon 1/3/22	Fri 1/28/22
10			**IST**	**195 days**	**Mon 8/30/21**	**Fri 5/27/22**
11			VF-11 facility prep	23 wks	Mon 8/30/21	Fri 2/4/22
12			HiVHAc IST	6 wks	Mon 2/7/22	Fri 3/18/22
13			Test report	4 wks	Mon 3/21/22	Fri 4/15/22
14			Algorithm updates [CPE]	10 wks	Mon 3/21/22	Fri 5/27/22
15			**ENVIRONMENTAL TESTING**	**95 days**	**Mon 3/21/22**	**Fri 7/29/22**
16			EMI / EMC	3 wks	Mon 3/21/22	Fri 4/8/22
17			Vibe / shock	3 wks	Mon 4/11/22	Fri 4/29/22
18			PDU examination [CPE]	4 wks	Mon 5/2/22	Fri 5/27/22
19			Thermal-vacuum	5 wks	Mon 5/30/22	Fri 7/1/22
20			Test report	4 wks	Mon 7/4/22	Fri 7/29/22
21			**POST-ENVIRONMENTAL TEST**	**165 days**	**Mon 7/4/22**	**Fri 2/17/23**
22			**IST**	**65 days**	**Mon 7/4/22**	**Fri 9/30/22**
23			HiVHAc+	3 wks	Mon 7/4/22	Fri 7/22/22
24			XR-5	3 wks	Mon 7/25/22	Fri 8/12/22
25			SPT-140	3 wks	Mon 8/15/22	Fri 9/2/22
26			Test report	4 wks	Mon 9/5/22	Fri 9/30/22
27			**Duration Functional Test**	**140 days**	**Mon 8/8/22**	**Fri 2/17/23**
28			Facility prep	8 wks	Mon 8/8/22	Fri 9/30/22
29			Extended HiVHAc+	16 wks	Mon 10/3/22	Fri 1/20/23
30			Test report	4 wks	Mon 1/23/23	Fri 2/17/23
31			**CLOSEOUT**	**50 days?**	**Mon 1/23/23**	**Fri 3/31/23**
32			PDU commercialization package [CPE]	10 wks	Mon 1/23/23	Fri 3/31/23
33			TDM final report		Fri 3/31/23	



"Key" Commercialization Documents

- Requirements document - (CPE and NASA)
- Specification document - (CPE and NASA)
- CDR package - (CPE and NASA)
- Worst Case Analysis (WCA) package - (CPE)
- Stress analysis package - (CPE)
- Thermal analysis package - (CPE)
- Radiation assessment and tolerance report - (CPE)
- Structural analysis package - (CPE and NASA)
- Bill of Materials (BOM) - (CPE)
- Qualification test package - (NASA and CPE)
  - Functional
  - EMI / EMC
  - TVAC
  - Vibe / Shock
- Integrated test package - (NASA and CPE)
  - HiVHAc+
  - XR-5
  - SPT-140
  - HERMeS